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Power oscillation damping supported by wind power: A review

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ABSTRACT

As a consequence of technological progress, wind power has emerged as one of the most promising renewable energy sources. Currently, the penetration level of wind energy in power systems has led to the modification of several aspects of power system behaviour including stability. Due to this large penetration, transmission system operators have established some special grid codes for wind farms connection. These grid codes require wind farms to provide ancillary services to the grid such as frequency regulation and reactive power regulation. In the near future, the capability of damping system oscillations will be required. For this reason, the influence of grid-connected wind farms on system oscillations is reviewed in this paper, focusing on the contribution or damping of power system oscillations, and on inner wind turbine oscillations.

Contents

1. Introduction

As result of worldwide environmental concern, reducing greenhouse gas emissions has become one of the most important

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Nomenclature

Acronyms

AVR	automatic voltage regulator
BR	breaking resistor
CCP	common coupling point
DDSG	direct drive synchronous generator
DFIG	doubly fed induction generator
EPSO	evolutionary particle swarm optimization
FACTS	flexible AC transmission system
FMAC	flux magnitude and angle controller
FRCIG	full rate converter induction generator
FRCWT	full rate converter wind turbine
FSWT	fixed speed wind turbine
FSWT-PMSG	fixed speed wind turbine—permanent magnet synchronous generator
FSWT-SCIG	fixed speed wind turbine—squirrel cage induction generator
HVDC	high voltage direct current
MPPT	maximal power point tracking
PLL	phase locked loop
PMSG	permanent magnet synchronous generator
PSO	particle swarm optimization
PSS	power system stabilizer
SCIG	squirrel cage induction generator
SCIG-WT	squirrel cage induction generator-wind turbine
SMES	super-conducting magnetic energy storage
STATCOM	static synchronous compensation
SVC	static var compensator
VSC-HVDC	voltage source converter—high voltage direct current
VSWT	variable speed wind turbine
VSWT-DDSG	variable speed wind turbine—direct drive synchronous generator
VSWT-DFIG	variable speed wind turbine—doubly fed induction generator
VSWT-FRCIG	variable speed wind turbine—full rate converter induction generator
WT	wind turbine

issues as was agreed in the Kyoto protocol [1]. Moreover, the European Union promotes the so-called 20–20–20 Target plan which aims to reach 20% energy efficiency improvement, to reduce 20% greenhouse gas emissions and to obtain, at least, 20% of its energy consumption from renewable sources by 2020 [2].

Wind power is rapidly increasing its presence in the power generation mix as one of the most promising renewable power source [3]. For many countries wind power has already become an important electricity source, e.g., Denmark, Portugal, Spain and Germany. The percentage levels of power provided by wind sources (the penetration levels) are 21%, 18%, 16% and 9%, respectively [4].

Due to this increment in wind power generation share, power systems stability and reliability may be affected. The characteristics of wind farms are substantially different from conventional power plants, such as hydraulic, nuclear or thermal [5,6]. These facts have led to the establishment of grid codes regarding wind farm connection, and their integration in the grid [7–9]. According to these codes wind farms must comply with requirements including voltage sag ride through capability [10,11], frequency regulation [12,13], and active and reactive power regulation [14,15]. In the future more wind farm contribution will be required by the system operators. The capability to damp power system oscillations will play an important role. There is a draft of the new Spanish grid code for wind power in which reference has already been made to inertia emulation and power oscillation damping [16].

The stability of power systems is related to the electromechanical interactions and the behaviour of the generators connected to the grid. Therefore, the influence of wind power penetration on the power system is an important issue to be studied [17]. It is important to analyse wind power behaviour under different wind power technologies and controls, as they present different dynamic characteristics causing different effects on the grid [18,19]. The contributions to power system oscillations damping have been studied considering different technologies, e.g., HVDC links and their controllers [20–25], by means of flexible AC transmission systems (FACTS) [26–28] and using wind farms [14]. This paper aims to discuss wind power impact on small signal stability and to provide a review of the different control methods for wind turbines (WTs) to damp both inner and power system oscillation modes.

This paper is organized as follows. In Section 2, a brief overview of power system stability concepts and the mathematical basis are presented. The impact of different wind turbine technologies in power system oscillations is analysed in Section 3. In Section 5, the methods proposed to damp out inner oscillations of the wind turbine are presented. The capability of wind farms to provide an extra power delivery to damp power system oscillation is discussed in Section 5. Finally, in Section 6, the conclusions are outlined.

2. Power system stability

Power system stability can be defined as the ability to maintain equilibrium during normal conditions and to recover an acceptable equilibrium after a disturbance [29,30].

Power system stability can be classified according to the response of the system to a fault [31] (Fig. 1).

- Rotor angle stability is concerned with the ability of the interconnected synchronous machines of a power system to maintain or restore equilibrium between electromagnetic torque and mechanical torque, and also to keep the synchronization between them.

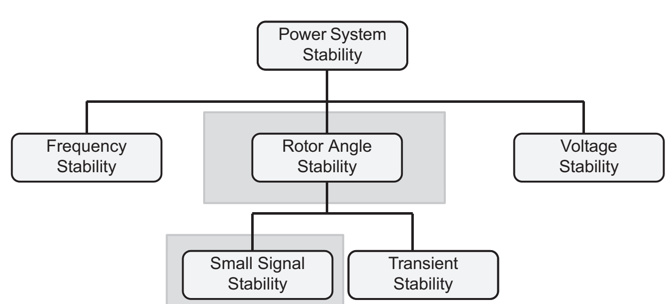

Fig. 1. Classification of the power system stability concepts.

- Frequency stability can be defined as the capability of a power system to recover the balance between the system generation and the load, with minimum loss of load.
- Voltage stability refers to the capability of a power system to maintain the steady state of all bus voltages both under normal operating conditions and after a disturbance.

Depending on the particular fault, rotor angle stability can be classified in two different groups: transient stability and small signal stability. Transient stability is related to the ability of the power system to maintain synchronism when it is subjected to a severe disturbance, such as a short circuit on a transmission line. The effect of small disturbances on the variables of the system is considered in small signal stability analysis. Small disturbances can be, for example, minor changes in the load or in the generation of the power system [29].

The study of small-signal stability may result in two different response modes such as non-oscillatory or aperiodic mode due to lack of synchronizing torque, and oscillatory mode due to lack of damping torque. The synchronizing torque is the component of torque change in phase with the rotor angle perturbation while the component of torque in phase with the speed deviation is the damping torque. The aperiodic problem has been largely solved by the use of automatic voltage regulators (AVR) in the generators. Oscillation modes are usually cancelled by means of power system stabilizers (PSS).

The small-signal modes of oscillation can be classified as [32,33] follows:

- Power system oscillations:
  - Inter-area modes: 0.1–0.7 Hz.
  - Local modes: 0.7–2 Hz.
- Machine oscillations >2 Hz:
  - Drive-train modes.
  - Control modes.

This classification permits to identify the causes of the oscillations and to propose damping control strategies.

Next, some background material about small signal stability is introduced to ease understanding of the rest of the paper content.

2.1. Mathematical basis of small signal stability

Power systems are nonlinear dynamic systems usually described by a set of nonlinear differential equations together with a set of algebraic equations, i.e.,

$$\dot{x} = f(x,u),$$

$$y = g(x,u), \tag{1}$$

where $x = [x_1, x_2, \ldots, x_n]^T$ is the vector of the state variables, $u = [u_1, u_2, \ldots, u_m]^T$ is the vector of the system inputs, $y = [y_1, y_2, \ldots, y_r]^T$ is the vector of the system outputs, and $f = [f_1(x,u), f_2(x,u), \ldots, f_n(x, u)]^T$ and $g = [g_1(x,u), g_2(x,u), \ldots, g_n(x, u)]^T$ are the vectors of nonlinear functions.

For a small signal stability analysis, the system (1) is linearized around an operating point [34]. Then, the power system can be written as a linear system:

$$\Delta\dot{x} = A\Delta x + B\Delta u,$$

$$\Delta y = C\Delta x + D\Delta u, \tag{2}$$

where Δ denotes a small variation with respect to the operating point, A is the state matrix, B the input matrix, C the output matrix and D is a matrix describing the direct connection between the input and the output.

The stability of the system can be analysed by computing the eigenvalues of matrix A of the system (2). The eigenvalues are the roots of the system characteristic equation $\det(sI-A)=0$, where det is the determinant. According to Lyapunov's first method, the small signal stability of a nonlinear dynamic system is determined by the location of the roots of the characteristic equation [35]. Each eigenvalue can be expressed as

$$\lambda_i = \sigma_i \pm j \cdot \omega_i, \tag{3}$$

where σ_i and ω_i determine the response of the system as follows:

When $\sigma_i < 0$ for all i, the system is asymptotically stable.
When at least in one of the eigenvalues, $\sigma_i > 0$, the system is unstable.
When at least in one of the eigenvalues, $\omega_i \neq 0$, the system has an oscillatory response.
When $\omega_i = 0$ for all i, the system has a non-oscillatory response.

Therefore, from the evaluation of the eigenvalues, system stability can be determined and also if the power system may present any type of oscillation. The damping ratio ($\xi_i = -\sigma_i/\sqrt{\sigma_i^2+\omega_i^2}$) permits to state how damped are the oscillation modes.

From the eigenvalues, the right eigenvector ($A\Phi_i = \lambda_i\Phi_i$), the left eigenvector ($\Psi_i A = \lambda_i \Psi i$) and the participation factor ($P = [p_1, p_2, \ldots, p_i]$, where $p_i = [p_{1i}, p_{2i}, \ldots, p_{ni}]^T$ and $p_{1i} = \Phi_{1i}\Psi_{i1}$) can be computed [36]. The participation factor permits to determine the contribution of each variable state to a particular eigenvalue.

3. The impact of wind farms in power system oscillations

In this section, the influence of wind farms on the oscillation damping of power systems is analysed. In recent years, several researchers have analysed the effects of oscillatory modes from two different points of view: oscillation modes of wind farms against power systems and inner oscillation modes of wind turbines. Most of the research in the literature considers equivalent models of the wind farms to emulate an aggregated behaviour in just one big wind turbine connected to the power system [37]. However, in some cases, this approach is not the most appropriate to reduce the wind farm to one-equivalent machine [38]. For example, to determine the oscillatory behaviour of the wind turbine components, it is usually necessary to analyse a single wind turbine against an infinite grid.

3.1. Oscillations in power system with wind farms

Wind turbines are generally not synchronously connected to the grid; hence they do not participate in electromechanical oscillations. Wind power itself does not induce new low frequency oscillation modes into power systems because their generator technologies do not engage in power system oscillations [39–41].

Due to the rapid increment of wind power penetration in power systems, it is important to analyse how this fact could affect the dynamic behaviour of the power systems. Several researchers divide this analysis not only by the penetration level, but also by changes in the system, such as the substitution of conventional generators by wind farms or the location of wind farms in different power system buses [14,42,43].

Here, in order to study the dynamic effect of main wind turbine technologies on the grid (Fig. 2), the study is divided into fixed speed and variable speed wind turbines.

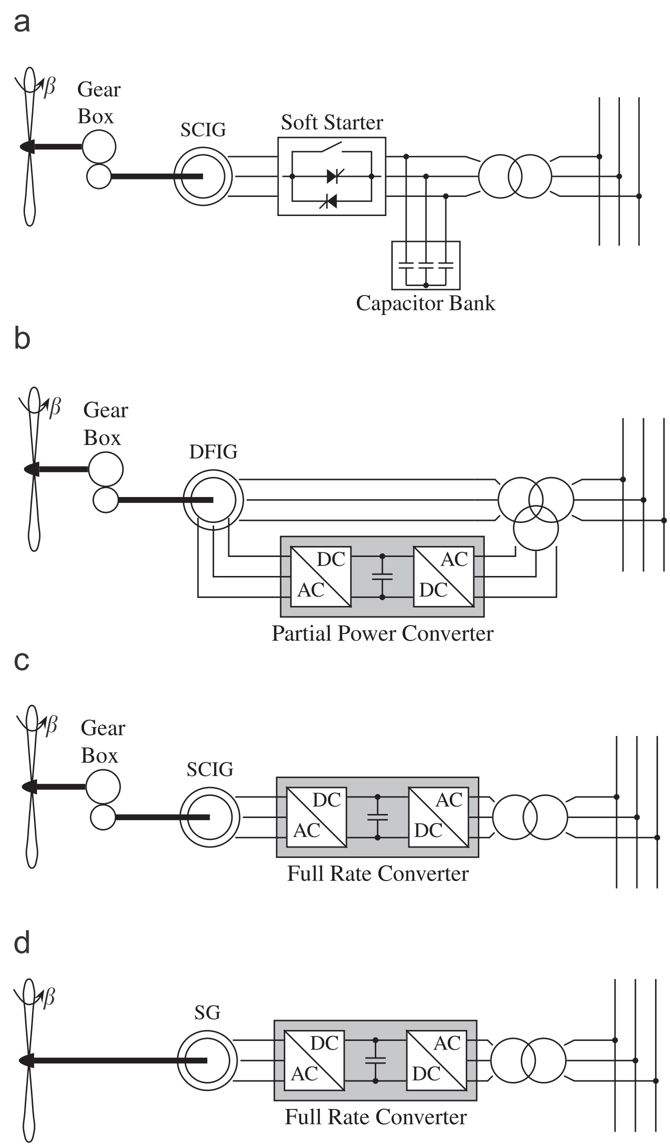

Fig. 2. Current main wind turbine technologies. (a) Squirrel cage induction generator—fixed speed, (b) doubly fed induction generator—variable speed, (c) full rate converter induction generator—variable speed, and (d) direct drive synchronous generator—variable speed.

3.1.1. Power system with fixed speed wind turbines

According to [14,17,39], fixed speed wind turbines (FSWT), understood as wind turbine driving squirrel cage induction generators (SCIG-WT) (Fig. 2(a)), improve the damping of power system oscillation modes. Moreover, due to their asynchronous nature they do not engage in power system oscillations nor do they induce new oscillatory modes [39]. It is agreed that SCIGs show better damping contribution on inter-area modes than on local oscillation modes [39,42,44–47].

However, some studies reveal that there are special situations where the impact of FSWT could have a detrimental effect on the oscillatory behaviour of the power system, e.g., the full load condition of the wind turbines in a weak grid [42,45], the penetration level in the power systems [17], the connection strength of the tie lines [48] or the location of the wind farm [47].

Although SCIG is the most common generator in FSWT, there are others, like permanent magnet synchronous generators (PMSG) which may engage in power system oscillations since they are synchronous generators directly connected to the grid like conventional power generators. FSWT-PMSG could have stability problems when a disturbance occurs in the power system [49].

3.1.2. Power system with variable speed wind turbines

Variable speed wind turbines (VSWT) are partially or totally decoupled from the grid by a power converter regulating the power delivered by the WT. As a result, power system oscillations do not affect the wind turbine [17,50].

Unlike FSWT, the influence of VSWT on power system oscillations does not draw a clear answer. In order to analyse the impact of VSWT on electromechanical oscillations, there are some important factors to be considered including wind turbine technology used, control mode of the VSWT and wind power penetration [51].

VSWT technologies can be divided on doubly fed induction generators (DFIG) and full rate converter wind turbines (FRCWT) as shown in Fig. 2(b)–(d). This classification is used in order to analyse the impact of VSWT technologies on low frequency oscillations.

DFIG is the most analysed VSWT because it is the most common technology. Researchers study the influence of the general DFIG-scheme without considering the possible impact of the control on power systems have come to divergent conclusions. Some authors have concluded that DFIGs can enhance power system damping [14,39,43,52], regardless of the wind farm location [47,53] or that DFIGs have even been able to provide good damping performance into a weak area of the grid [54,55]. However, in other studies it is shown that DFIGs can decrease the damping of the inter-area oscillation mode [44], or reduce the damping in special cases such as when the increment of wind power contributes to an increase in the power system stress [56,57] or when its increase reduces the damping because it can collapse weak interconnection lines [58].

Some results reveal that VSWT-DFIGs are able to interact with the PSS of synchronous machines. These WTs can damp initial oscillations of the power systems for small disturbances but may decrease voltage stability under large disturbances, in comparison with other synchronous machines [59].

When comparing control methods in the analysis of the interaction between the VSWT-DFIG and the power system, the conclusions are quite different. WTs with power factor control, the oscillation modes could be slightly better damped [40,60] or have a detrimental effect on the damping [55,61]. On the other hand, WTs with frequency control help to enhance damping of the oscillatory modes [40,60]. This is because the rotor oscillations are observable from the grid frequency signal. It should be noted that all previous control methods mentioned do not regulate reactive power.

The effect of an additional voltage control loop to regulate reactive power could be detrimental depending on the particular choice of the control parameter and also on the location on the measurement point [55,62]. The interaction of the voltage control with the frequency control may achieve a slight improvement according to [60]. In Table 1, a summary of the influence of VSWT-DFIG is classified by the control used.

Within FRCWT technologies are direct drive synchronous generators (DDSG) (Fig. 2(c)) which is the most common, and full rate converter induction generators (FRCIG) (Fig. 2(d)). DDSGs have been categorized by some authors in the same group as DFIGs [17,42], therefore, they concluded that the impact in power systems oscillations of DDSG is similar to DFIG. Again, conclusions are divergent, for instance, a damping enhancement of the power system oscillations is reported in [46,64]. On the contrary, the damping could be decreased if a power factor control mode is

Table 1
Summary of results on the impact of the DFIG controls on power system oscillations.

Control	Influence
Power factor	Small enhancement of the power system damping [40,60] Some negative effects on the damping of power system oscillations are reported in [55,61]
Voltage control	Optimization of voltage control constants with power oscillation constraints improves the damping [63] Sensibility to the control parameters, incorrect values may be detrimental to the damping [55,62]
Frequency control	Enhance the damping of the power system oscillations [40,60]

Table 2
Summary of results on the influence of wind power technology on power system oscillations.

Technology	Influence
FSWT-SCIG	Can improve damping of the power system [39,42,44,46,47] Can deteriorate oscillatory behaviour under special conditions [39,45,47,48]
FSWT-PMSG	Has problems in stability [49]
VSWT-DFIG	Can enhance power system damping [14,39,40,43,47,52–55,60,63] Can decrease the damping of inter-area oscillations modes [44,55–58,61,62]
VSWT-DDSG	Can improve oscillatory behaviour of the power system [46,64] Can affect negatively in oscillations [44,65,66]
VSWT-FRCIG	Can affect positively in power system oscillations [67,68]

used [44,65] or if a voltage control is introduced to regulate the reactive power [66].

In contrast, with FRCIGs, the damping of the inter-area oscillation is increased either by power factor control [67] or by voltage control [68].

There is alternatively variable speed wind turbine technology connecting a synchronous generator directly to the grid with a hydro-dynamically controlled gearbox [69]. In this technology, wind power penetration could be relevant, since it is a synchronous machine connected to the grid and thus is able to engage with power system oscillations.

Convergent results on the influence of wind power on power system stability are summarized in Table 2.

3.2. Inherent oscillations of wind turbines

In WTs there are several rotating elements and electrical devices interacting. Hence, it is interesting to investigate the oscillations that could appear in the machine or in the wind farm. A wind turbine has many inner oscillation modes, e.g., for-after tower movements. From an electrical point of view, only the torsional modes are important since they are the only ones that may affect the power system. Again, this study is divided in FSWT and VSWT.

3.2.1. Fixed speed wind turbines

In FSWT, the main oscillation modes are associated with the drive-train. Notice that the mechanical dynamics of the wind turbines must be described with at least a two-mass [70], or three-mass model [71], since a single-mass shaft models cannot properly represent mechanical oscillations.

Mechanical oscillations are critical since they induce fatigue stresses on the drive-train components, increasing the risk of damage to the mechanical system. Drive-train oscillation modes are dynamically dominant in the WT. These oscillation modes depend on the shaft stiffness, the network reactance, the rotor resistance and the operating slip.

Under normal operation, torsional oscillations are well damped since the slip curve of the induction generator acts as an effective damper [14,72]. However, the system can be lead to oscillate by different disturbances. For instance, the wind speed variations may excite these modes causing resonance phenomena at special gear ratios [73]. Moreover, an electrical disturbance close to the common coupling point (CCP) may provoke mechanical stresses [74,75]. Also, the torsional oscillations can be excited by the aerodynamics of the wind turbine [76]. Even, wind fluctuation in a specific speeds can cause drive-train oscillations to the wind turbine [77].

3.2.2. Variable speed wind turbines

In VSWT, besides the shaft, the power converter can also affect the inner oscillations. However, it can be noticed that the inherent oscillations of the machines does not dependent on VSWT technologies. These oscillations are mainly associated with the drive-train and with the converter [55,64,78].

In VSWT operating at constant generator torque, there is a slight damping provided by the induction generator in comparison with FSWT since the torque does not vary with the generator speed [14,72]. This fact implies that torsional oscillation modes in VSWT are less damped than in FSWT.

The interaction between these inner oscillations and different converter controls is interesting to analyse. Voltage control could present a poorly damped shaft oscillation mode for certain parameter setting [79]. Incorrect controller constants may cause an amplification of the oscillations during a fault in the CCP. Analysing this control configuration in more detail, a range of controllability and stability can be determined [80]. In [81,82], a study of the sensibility of the oscillation modes to different parameters is presented, e.g., wind speed and mechanical torque input, and the critical stability points, known as Hopf bifurcation, are determined.

In [83], the behaviour of different power control strategies, as in maximal power point tracking (MPPT) and power smoothing have been analysed. The first control has a positive effect on the oscillation damping of the generator, whereas power smoothing control has no damping effect.

A scheme giving an overview of the key points of the impact of wind farms on power system oscillations is shown in Fig. 3.

4. Damping control for wind turbine inner oscillations

In this section, the controllers designed to enhance the damping of torsional oscillations are analysed. This section is organized by the type of control that is used, such as mechanical and converter-based regulation.

4.1. Mechanical regulation

Inner oscillation modes of the wind turbine can be mechanically damped by regulation of the blades using the pitch control, by the inclusion of mechanical dampers in the wind turbine drive-train or by the inclusion of some external devices such as FACTS.

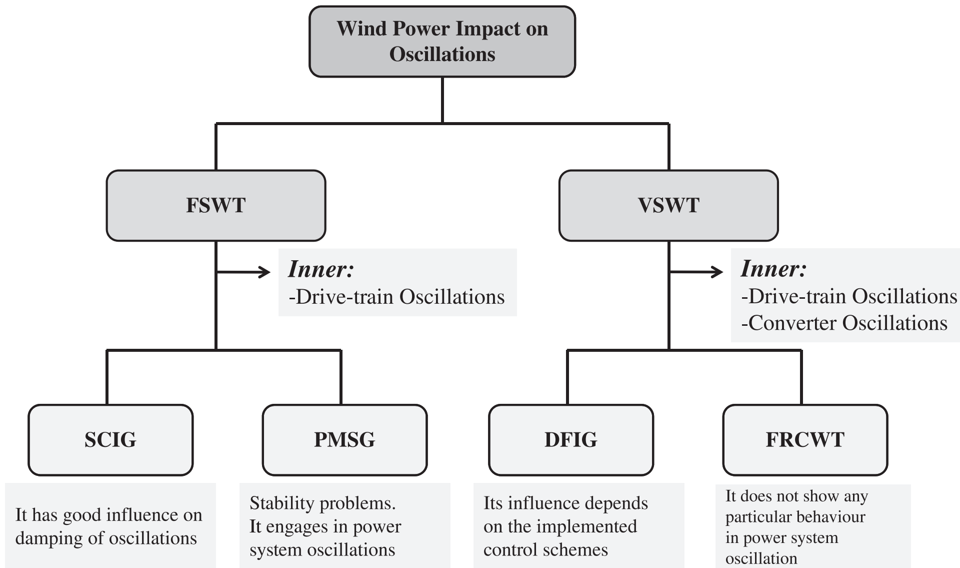

Fig. 3. Brief summary of the impact of wind farms on oscillations.

Generally, the mechanical stress suffered by the wind turbine (for instance torsional oscillation) is generated by a difference between the turbine and the generator torque. This difference could be produced by several causes, such as an electrical fault close to the wind turbine or wind gusts. This torsional oscillation could be smoothed by pitch angle control which reduces the torque in the turbine [84–86].

Direct-drive wind generators which directly couple the generator to the wind turbine, eliminate the requirement of a gearbox. However, they make the conventional generator design of the windings ineffective to damp oscillations, requiring a damper in the wind turbine [87]. In this paper, a spring and a mechanical damper are included to enhance the damping of the mechanical oscillations.

Since mechanical regulation is slow and limited in FSWT, the use of external devices is necessary to obtain a faster response to faults. In [88,89] is stated that the torsional oscillations can be further damped by including a STATCOM device rather than using only pitch angle control. In addition, a STATCOM controlled to mitigate SSR and to damp torsional oscillations simultaneously is presented in [90].

4.2. Converter-based regulation

There are some research developments regarding inner oscillations of the wind turbine and their damping using a control of the converter. A PID controller for drive-train oscillation damping included on the generator torque regulation is presented in [14,72,91]. From these documents, it can be concluded that a PID torque controller could effectively help to enhance torsional oscillation damping of the wind turbine on the desired frequencies. This controller can be seen as a band-pass filter of the form

$$G\frac{2\xi\omega s(1+s\tau)}{s^2+2\xi\omega s+\omega^2}, \tag{4}$$

where G is the gain, ω is the frequency that must be close to the frequency to be damped, ξ is the damping of the controller and τ is used to compensate the time delays in the system. The parameters can be properly tuned using a root locus plot [72].

In [92] a conventional PSS scheme has been introduced to regulate the DC link using the machine speed as input. Also, a minor control loop composed of a high-pass filter and a second-order controller has been proposed for VSWT [93]. This proposal is cheap, requires less parameters identification and is easy to implement on the actual controls. A comparison of pitch control with gain scheduling and a drive train damper has been demonstrated in [94]. This study shows that the controller is able to achieve a significant reduction of the oscillations in the drive-train and to reduce the possibility of fatigue damage. In order to reduce the mechanical loads in the drive train, a self-tuning control scheme acting on the pitch actuator and on the power converter has been proposed in [95]. This adaptive controller varies the parameters of the torque controller to minimize the torque variation of the drive train. In [96] a sliding mode control is proposed to optimize the power efficiency and the torsional dynamics. This paper presents a controller that provides a compromise between power extraction efficiency and torque oscillation smoothing.

Wind turbine inner oscillations are an important issue, not only due to the delivered power quality but also because of the stress suffered by the mechanical system of the wind turbine, mainly the drive-train. Some methods to damp drive-train oscillations have been patented, for example, a vibration damper designed to damp drive-train oscillations with a peak detector in order to reduce the tower oscillation effect [97] and a moment corrector by means of the rotational speed error [98]. In [99], an implementation of a new controller is proposed to avoid the use of Fourier transform that results inaccurate during frequency variations. Also a method to improve the quality of the power delivered to the grid by means of DC-link voltage regulation is presented in [100].

Fig. 4 provides a summary of the regulation proposals of the torsional oscillations following the section structure.

5. Control of wind farms for enhancing the damping of power system oscillations

In this section, the active contribution of wind farms to damp the oscillations suffered by the power system using FSWT and VSWT is analysed. VSWT can regulate the power delivered to the grid by means of power converters, which can independently control active and reactive power using vector control [101] or flux magnitude and angle controller (FMAC) [102], and using

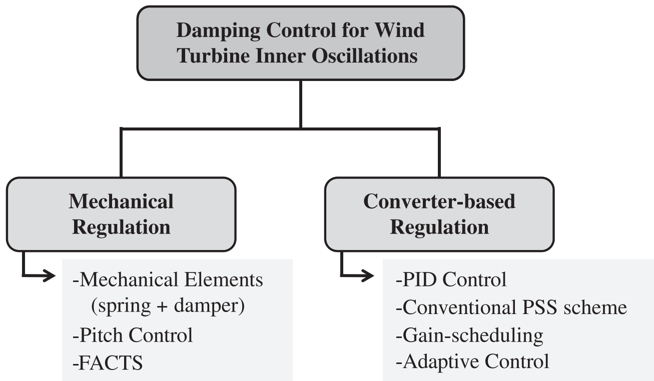

Fig. 4. Summary of control proposals to damp wind turbine inner oscillations.

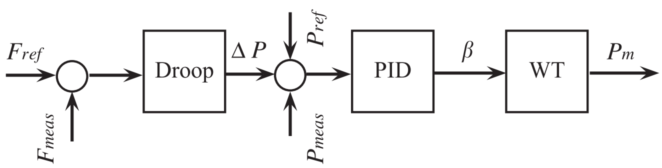

Fig. 5. PID pitch angle controller scheme.

properly a pitch angle control, whereas in FSWT, only the pitch angle control can provide power regulation [84].

This section has been organized by the type of extra-regulated power delivered to the grid, such as active, reactive or active–reactive power regulation.

5.1. Active power regulation

The regulation of active power is the logical and direct approach to damp power system oscillations because the oscillations are produced by active power differences between generation and consumption. Therefore, these oscillations can be reduced by controlling active power delivery.

Active power can be regulated by means of mechanical systems or by using power converters.

5.1.1. Mechanical regulation

It is well known that mechanical regulation of wind turbines is slower than the control of electrical variables [14,84]. Hence, its effect can be noticed with some delay. Mechanical regulation to counteract power system oscillations is mainly focused on pitch angle control and is more common in FSWT [103].

The most simple control alternative to damp out power oscillation consists of a PID controller acting on the pitch angle, where the controller input is the frequency error [104]. This scheme can be seen in Fig. 5, where F_{meas} and F_{ref} are the measured frequency from the grid and the reference frequency, respectively, ΔP is the power deviation calculated by a droop controller from the frequency deviation, P_{meas} is the measured power from the WT and P_{ref} is the reference power. β is the pitch angle, and P_m is the mechanical power of the WT. Another more complex solution is the fuzzy logic controller also acting on the pitch angle which is shown in Fig. 6. This controller can deal with the nonlinearities and the non-accurate knowledge of the system [105].

Pitch angle control proposals for other kinds of grid support may be implemented with the purpose of damping power system oscillations. For example, a pitch angle regulation for frequency control, which uses the frequency error as input and delivers a

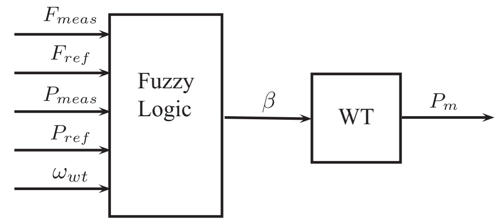

Fig. 6. Fuzzy logic pitch angle controller scheme.

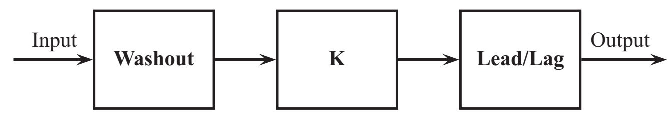

Fig. 7. Conventional PSS scheme.

pitch angle variation, could be suitable to reduce these oscillations [106–108].

5.1.2. Mechanical and external regulation

Although pitch control systems are capable of improving wind farm stability, they may act too slowly to compensate some of the oscillations. Thus, as in FSWT there is only the possibility of power regulation (pitch angle control), the use of external equipment (FACTS) is required to increase its damping contribution. Such equipment could include dynamic breaking resistors (BR) which only regulate active power, a static synchronous compensator (STATCOM) which can control reactive power and superconducting magnetic energy storage (SMES) which is able to regulate both active and reactive power at the same time [109]. In [110] external regulations are shown to be more effective in the wind farm stabilization than pitch angle control. In [111] is presented that the system is better damped by using simultaneously STATCOM and pitch angle control, than by using uniquely a STATCOM.

5.1.3. Power converter regulation

In contrast with mechanical regulation, active power regulation by means of power converter is a fast acting control. Currently, the majority of the controller proposals to damp power system oscillations are of active power modulation in the converter.

As in frequency control [112], the first steps in additional power oscillation damping controller for wind power is to copy the power system stabilizer from the synchronous generators [113], and to introduce it into the wind turbine controller.

The main function of a power system stabilizer is to damp low frequency oscillations. Commonly, a PSS consists of three blocks as Fig. 7 shows. The washout block, a proportional controller and the lead/lag block. The PSS input can be any signal affected by the oscillations of the synchronous machines. However, machine speed, terminal frequency or power is normally used. The output signal is usually a voltage variation in the excitation system. The washout filter is a high pass filter that rejects the low frequencies and steady states of the input

$$T_w(s) = \frac{s\tau_{wh}}{1+s\tau_{wh}}. \qquad (5)$$

The PSS is expected to respond only to transient changes. The selection of the washout time constant value (τ_{wh}) depends on the type of modes under study. The proportional controller K determines the amount of damping introduced by the PSS. Finally, the lead/lag block consists of a phase compensator. It provides the desired lead or lag phase in order to reduce rotor oscillations.

This dynamic compensator is usually made up of two lead–lag stages as follows:

$$T_{ph}(s) = \frac{(1+s\tau_1)(1+s\tau_3)}{(1+s\tau_2)(1+s\tau_4)}. \quad (6)$$

The time constants (τ_1, τ_2, τ_3 and τ_4) are selected in order to provide a phase lead in the frequencies of interest.

Most of the schemes used in the converter control are based on vector control, whereas a few are based on flux magnitude and angle control (FMAC). Considering this fact, the extra active power loop is divided according to their control scheme.

For a FMAC control scheme in a DFIG wind turbine, in [102,114] the use of conventional power system stabilizer controls with the angle variation as output and use the slip of the DFIG as input has been proposed. Similarly, other alternatives include the use of conventional PSS but with the introduction of the electrical stator power as input instead of the slip [115], or even choosing a terminal voltage signal, which has good visibility of the inter-area oscillation of the power system as input and generating an active power variation signal [116]. All input and output signals presented above in the conventional PSS scheme present proper behaviour enhancing power system stability. However, some authors have expressed some doubts about the influence of tower shadow and wind variation on the performance of a conventional PSS controller for DFIG wind turbines with various inputs, such as electrical generating power, rotor speed and grid frequency [117]. The DFIG wind turbine presents a good damping response with all the inputs, although the rotor speed was adversely influenced by the torque variations due to the tower shadow which amplifies the PSS response and consequently the turbine torque, whereas wind variation effect is almost filtered.

Optimal control options have also been proposed. The idea is to tune the controller parameter to minimize some criteria. Among these alternatives, in [118] a genetic algorithm (in particular, a bacteria foraging algorithm) is used to adjust the parameter control of DFIG. Implemented in a DFIG connected to an infinite bus, [119] gives promising results when the optimal tuning is done for any sub-synchronous speed. However, if the parameters are optimized for any super-synchronous speed, the controller response is poorer than for the other speed cases [119]. A mixed control of eigen-structure assignment and a multi-objective nonlinear optimization method for the conventional PSS have been developed in [120]. This controller with multi-input signal, speed and stator power can serve to mitigate the inner oscillations of the DFIG and to damp out the power system oscillations.

Also, a FMAC control scheme in a full power converter with a conventional PSS scheme is included in the grid-side converter controller, where the grid frequency is the input and the voltage angle variation is the output in [121]. It is shown that the oscillations are better damped when the power oscillation damping controller is added in the wind turbine controls.

Conventional PSS has also been implemented for vector control schemes. The oscillation damping achieved by these schemes have been studied for several input–output pairs and optimizing controller parameters. Taking the voltage variation as output in the active power loop, as is usual in the control of the excitation in synchronous machines, the performance of the scheme has been evaluated using different inputs including the speed of voltage angle, the active power in one of the lines and the difference in rotor speed of the synchronous generators [122,123]. These studies reveal that although all of the proposals are able to improve the damping, the use of power in one of the lines presents much better results. Other authors, who also use the conventional PSS, have proposed a simple tuning procedure to adjust the PSS parameters selecting the bandwidth of the controller [124]. In this scheme, the voltage of the wind farm terminal is chosen as input and a variation of the power reference as output.

Some researchers have proposed a reduced version of the conventional PSS, comprising a filter and a proportional controller with the grid frequency as input and the power reference as output [125]. The proposed scheme has exhibited an effective damped behaviour of the inter-area oscillations.

Other authors have used root locus methods to design the controllers. Here, the idea is to add pole-zero pairs in order to attract the root locus towards more damped locations in the left-hand side of the complex plane, ensuring stability. These methods permit the controller to improve just one oscillation mode with a simple control scheme [126]. In order to affect more oscillatory modes, a more complex controller is required [127,128]. These methods are effective to damp desired oscillation modes. However, a good knowledge of the global system is necessary.

Optimization algorithms have been introduced to overcome the tuning problem of WT controllers. Particle swarm optimization (PSO) and the evolutionary particle swarm optimization (EPSO) method attempt this [63,129].

A vector control scheme in a PMSG wind turbine with classical PSS has been analysed in [83] under different active damping controls such as power regulation, DC-link regulation, torque regulation and an improved torque regulation, where the outputs are active power reference variation, DC link voltage reference variation and torque variation, respectively. All of the active damping schemes have generator frequency as input. All the schemes present a good damping performance, but some of them need a phase compensator to damp out some power oscillations, except for power regulation where the input and the output are directly in phase.

A grid frequency based PSS for variable speed wind turbines has been proposed [130–133]. It is shown in Fig. 8 where ω_{wt} is the speed of the wind turbine, Δf_{grid} is the grid frequency deviation, P_{wpss} is the output of the PSS controller, P_{wind} is the power calculated by the speed controller and P_{mech} is the mechanical power from the WT. It can be implemented under different control schemes such as FMAC or vector control, and its output is added to the speed regulation output. Thus this control also is able to affect the turbine regulations. It is important to note that this control is simpler than conventional PSS. Moreover, it can be implemented in wind turbines without additional costs and it only requires local variables, obviating the use of wide-area communication systems.

Although, active power regulation is a good approach to damping out the power system oscillations, it can negatively affect drive-train oscillations [134,135,128].

A classification of the different input–output pairs proposals for the conventional PSS controller can be seen in Table 3. The inputs are the electrical power P_e, the voltage in the WT terminal V_{WT}, the frequency of the grid f_{grid}, the electrical power in one of the lines of the power system P_{line} and the difference of the angle

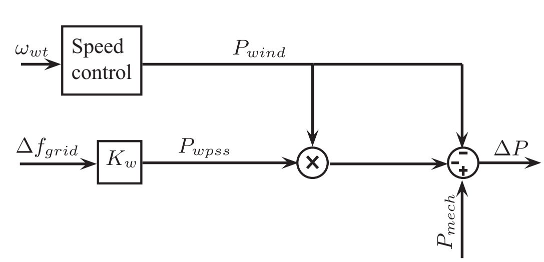

Fig. 8. Simple power damping controller scheme.

Table 3
Classification of conventional PSS proposals depending on inputs and outputs.

Input	Output		
	$\Delta\delta$	ΔP_{ref}	ΔV_d
Rotor speed/slip	[102,114,115,117]		[122,123]
P_e	[115,117]		
V_{WT}	[116]	[124]	
f_{grid}	[117,121]	[125]	[122,123]
P_{line}			[122,123]
$\delta_i-\delta_j$			[122,123]

between two synchronous machines $\delta_i-\delta_j$. The outputs are a voltage angle variation for the FMAC control scheme $\Delta\delta$, a power reference variation ΔP_{ref} and a d-component voltage variation for the vector control scheme ΔV_d.

5.2. Reactive power regulation

There are only a few results reporting the use of reactive power regulation to damp the oscillations in power systems. Most of them are applied in DFIG wind turbine technology using vector control.

As in the active power regulation case, the implementation of a conventional PSS scheme in the reactive power loop has been studied. The conventional PSS scheme has been evaluated by using a voltage variation as output and different inputs such as local signals (e.g., speed of voltage angle) and remote signals (e.g., power in one of the lines and the difference in rotor speed of the synchronous generators) [122,123]. From these studies, it is possible to conclude that wind farms with an additional controller are capable of damping oscillations. All proposed alternatives achieve a good damping of power system oscillations, but the use of local signals as input presents the best performance.

Some researchers agree that active power modulation affects electromechanical torque of the wind turbine, whereas reactive power modulation does not since the converter acts similarly to a static var compensation (SVC) [127,128]. The controller uses the angle difference between two groups of synchronous generators and an increment in reactive power reference as output. It is designed by root locus methods in order to place the zeros and the poles of the system in the desired location of the complex plane. The results presented in [136] indicate that this alternative is effective to damp the oscillations.

5.3. Active and reactive power regulation

Active and reactive power regulation can be achieved by a VSWT converter control which allows modulation of the quantity of active and reactive power delivered by the wind farm.

5.3.1. Power converter regulation

As mentioned above, the power converter can modulate active and reactive power independently in order to damp oscillation. Hence, it is possible to propose schemes based on simple control tools with two power loops independently designed but acting simultaneously.

Similar to cases previously discussed, there are results using conventional PSS controllers in both active and reactive loops [137]. In this work, different inputs are analysed including the deviation of generator rotor speed (a remote signal) and the frequency deviation of the DFIG terminal voltage (a local signal). In all cases, these alternatives are effective to damp the network oscillations without affecting the DFIG shaft oscillation mode, although its impact is much more noticeable in cases where the remote signals are considered as input.

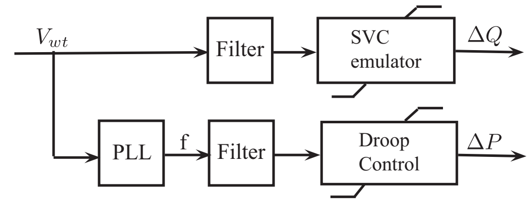

Fig. 9. Energy function approach controller scheme.

Another power damping controller design is based on FACTS and VSC-HVDC control methods to damp rotor oscillation of the conventional plants which are designed as a simplified conventional PSS scheme [138].

Finally, a method to find a mixed active and reactive control strategy is the energy function approach which is based on the second Lyapunov method. This control strategy is represented in Fig. 9, where V_{wt} is voltage of the wind turbine terminal and f is the frequency calculated by the phase locked loop (PLL) from the V_{wt}. The energy function (E) is given by

$$E = E_K + E_P,$$

$$\frac{d}{dt}E = \frac{d}{dt}E_K + \frac{d}{dt}E_P < 0, \qquad (7)$$

where E_K is the kinetic energy and E_P the potential energy.

The energy function can be determined by the classical model of the synchronous generators. The incremental active and reactive powers are computed from the derivative of this energy function. Notice that the derivative of the energy function must be negative to keep the system stable.

The active power law is usually determined by a kind of kinetic response emulation; whereas the reactive power law is commonly defined considering that the wind farm emulates the behaviour of a SVC. Classical droop control is used for active power regulation with different local signal inputs, for instance, the wind farm terminal voltage derivative [60] and the wind farm terminal frequency variation [138], whereas a nonlinear kinetic equation is performed using wind farm terminal angle speed and the wind farm terminal angle acceleration [139].

According to some studies, energy function control does not need coordination with other network controllers and its response does not depend on the location of the wind farm since the controllers are obtained from the equations which are independent of power systems [60]. Some authors conclude however that by using the same control approach the active power loop is most efficient when the wind farm is connected close to a synchronous power plant and the reactive power modulation is best when is located away from conventional generators [138]. Depending on the wind farm location the stabilizing control is able to damp either inter-area oscillations or intra-area oscillations [139].

A classification of the control proposals relating to both the control schemes and the regulated power is shown in Table 4. In Fig. 10 a scheme has been drawn giving a summary of the proposals of power oscillation controllers following the section structure.

6. Conclusions

In this paper, a review of the current research on the effect of wind farms on power system stability, showing both their influence on the oscillations such as in the power system and

Table 4
Classification of controller scheme proposals by affected power.

	Control					
Power	Conventional	Root locus	Lyapunov	Pitch angle	Pitch+ext. equipment	Optimization algorithm
Active	[102,114–117,121–124,134]	[126–128]		[103–105,109,110]		[118–120,129]
Reactive	[122,123]	[127,128,136]				
Active and reactive	[137,138]		[60,138,139]		[88,89,109–111]	

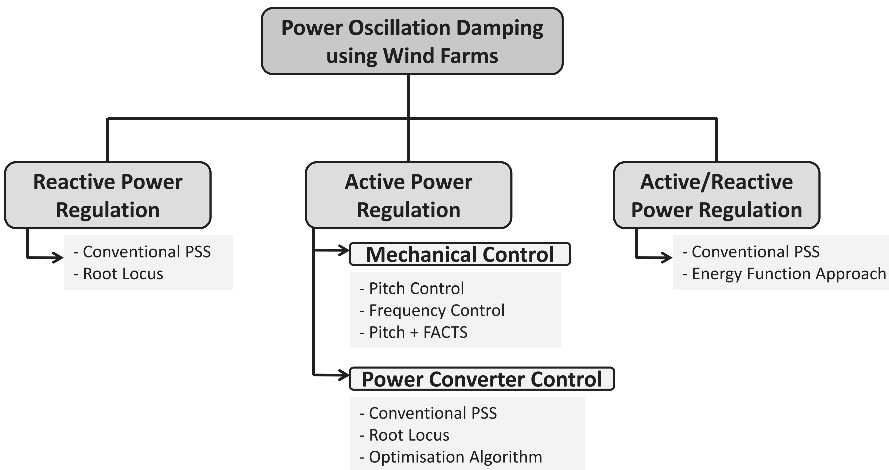

Fig. 10. Summary of power oscillation damping control proposals.

their inner oscillations. Their contributions to the improvement of the stability are evaluated and presented.

It is commonly accepted that wind farms cannot engage with power system oscillations since they usually include asynchronous generators and power converters. It is also accepted that FSWTs produce beneficial effects on the damping of the power system oscillations. On the contrary, the results for VSWT do not draw clear conclusions about their effects on power system stability. The results in case of VSWT depend on the control included in the wind farm. The power factor or voltage controls may have in general a detrimental effect on the damping, whereas frequency control can enhance power system stability.

Wind farms have their own oscillation modes. The modes associated with the converter and the drive-train modes mainly arise in the mechanical part of the wind turbine and may be amplified during a voltage fault. These oscillations can be damped by means of power converter control or by means of mechanical regulation with pitch control or mechanical elements.

A number of works have proposed the use of additional control loops in order to help to damp the power system oscillations. These controllers are based on three different principles: to vary the active power delivered to the grid, to modulate the reactive power delivered and to regulate the active and reactive power simultaneously. The reactive power control can only be done by acting on the power converter, whereas the active power control can be implemented using the power converter or pitch control system.

According to the work reviewed in this paper, a clear trend towards the use of active power control to improve the stability of power systems can be observed. Nevertheless, the results on reactive power control are promising and they should be studied carefully. The effect of reactive power regulation could be important for power systems due to its capacity to change the power flow of the busses having lower effect in drive-train oscillations.

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